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Fracture mechanics of creeping solids applied to pre-cracked NOL ring specimens to predict residual lifetime of high density polyethylene pipes

Laiarinandrasana[a,*], Devilliers[a,b], Gaudichet-Maurin[b], Brossard[b], Lucatelli[b,c]

[a] *Mines ParisTech, Centre des Matériaux, BP87, Evry Cedex 91003, France*
[b] *VERI, Chemin de la Digue, Maisons-Laffitte 78603, France*
[c] *CAE Caen, Laboratoire de Matériaux, 40 Avenue de la première armée française, Caen 14000, France*

Abstract

High Density Polyethylene (HDPE) is widely used for the distribution of drinking water and are exposed to an internal pressure due to water flow. Furthermore, when they are in contact with disinfectants, oxidation of HDPE occurs at the immediate surface of the inner wall. This leads to a decrease in the HDPE molar mass and consequently, to a hardening as well as an embrittlement of the material. The oxidised layer thickness seems to stabilize at 200 μm whatever the initial pipe thickness due to the diffusion of reactive species in the inner wall. Inspections with a scanning electron microscope (SEM) of the inner wall of pipes collected on site, after several years of service, showed a network of cracks . The most noxious (deepest) longitudinal crack propagates under the steady internal pressure until the complete failure of the pipe. The experimental investigations consisted of creep crack growth tests, carried out on an original geometry for this type of test using NOL ring. These specimens were cut from the pipes and an internal longitudinal crack implanted. Creep crack growth tests were performed at various net stresses and at various crack depth ratios. At the end of each test, the time to failure was recorded. Before applying the theory of fracture mechanics of creeping solids, 3D finite element simulations were carried out to assess the suitability of assuming plane strain conditions. To this end, a porous viscoplastic model was implemented into an in-house finite element code. A fracture criterion based on critical porosity allowed for the simulation of creep crack growth. The localization of the maximum damage at mid-thickness and the thickness reduction were well captured. In these conditions, the crack front curvature is located near the surface so that a 2D calculation with plane strain conditions can then be justified to determine the C* load parameter. The residual lifetime of a real pipe containing a longitudinal defect, under in-service loading was estimated by using the correlation between the time to failure and the C*-integral.

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* Laiarinandrasana Tel.: +33-1-60763064 ; fax: +33-1-60763150
E-mail address: lucien.laiarinandrasana@mines-paristech.fr

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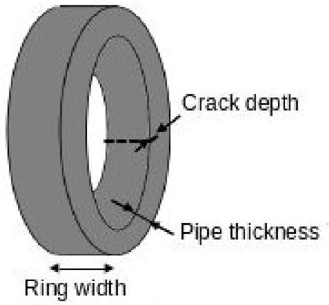

Fig. 1. Precracked NOL ring specimen for creep crack growth tests.

1. Introduction

High Density PolyEthylene (HDPE) is a material widely used for the distribution of drinking water. Pipes are subjected to an internal pressure due to the water flow. When the internal wall of HDPE pipes is in contact with disinfectants such as chlorine dioxide ClO_2, its oxidation occurs by a chain scission phenomenon. This leads to a decrease of molar mass and a development of a network of cracks. The motivation of the present work deals with the prediction of the residual lifetime of such pipes containing longitudinal internal cracks. Most of the methodology used to this end utilizes mechanical load parameters which do not take the time-dependent strain (viscoelastic or viscoplastic) into account. An attempt is made here to use the tools of fracture mechanics for creeping solids to achieve this goal. Indeed, the pipe is assumed to be under a constant internal pressure held for a long period of time. Therefore, in addition to double edge notched tensile laboratory specimens creep tests results, an intermediate specimen is proposed here: the precracked NOL ring specimen. Historically, the ring expanding test was first recommended by International Standard ISO 8495-8496 for characterizing thin metallic material tubes. The main purpose was then to measure the transverse properties of structural tubing. Devilliers et al. (2009) followed the recommendation of ASTM D 2290-04 standard dealing with the characterization of the apparent hoop tensile strength of plastic materials for structural tubing. To this end, tensile tests have to be performed on rings, cut from the pipe, by a split disk method (Laiarinandrasana et al. (2011a)). The novelty here is that the rings were precracked with an internal longitudinal defect. This precracked geometry was subjected to various fixed loads to determine the time to failure under creep loading.

2. Experimental procedure

2.1. Material and specimens

The material of interest was a high density polyethylene (HDPE) supplied by the VEOLIA company as extruded pipes. The main physico-chemical characteristics are summarized as follows: the melting point T_f = 127°C; the average molar mass M_n = 10.2 kg/mol; the Young's modulus E = 650 MPa. The studied HDPE exhibits an initial semi-crystalline microstructure composed of spherulites.The typical spherulite diameter has been determined to be about 10 μm and the index of crystallinity was estimated at 55 %.

Pipe dimensions were the following: length L = 500 mm, internal diameter Φ_0 = 31 mm and thickness t = 4.5 mm. Rings of 12 mm in width W were cut from these pipes. A precrack was introduced by pushing a cutter blade onto the internal wall of the ring. The initial crack depth a was precisely measured after creep test by scanning electron microscopy (SEM). The crack depth ratio a/t was one of the principal parameters used in this study. Only one side of the ring was precracked, in order to avoid creating a gap between double diametrical edge crack planes. Figure 1 shows a sketch of a precracked ring specimen.

2.2. Creep crack growth tests

Table 1. Details of creep crack growth tests on NOL ring specimens.

Laboratory	a/t	σ_{net} (MPa)	t_F (h)
CdM	0.35	10.6	0.9
CdM	0.34	9.4	0.3
CdM	0.43	8.6	79
CdM	0.57	8.9	2.7
CdM	0.56	7.9	19
CdM	0.24	9.2	167
CAE	0.56	9.2	3.5
CAE	0.30	9.3	33
CAE	0.48	10	4.9
CAE	0.35	9.3	21
CAE	0.51	9.2	34

The creep crack growth tests were conducted in two french laboratories, labelled CdM (Mines ParisTech) and CAE (Veolia company). The test conditions consisted of a fast loading to reach the prescribed load, then this load was maintained constant until the failure of the ring.
Each test was characterized by:

- the ring crack depth ratio a/t, where a is the crack depth and t the thickness of the ring;
- the applied net stress σ_{net} equal to the applied load divided by net section $((t + (t - a)) \times W)$, where W is the width.

Table 1 summarizes the tests that were selected for this contribution. Tests where $a/t \leq 0.2$ were not shown here because they exhibited small cracks effects.

2.3. Experimental results

The experimental results are depicted in the last column of Table 1. The time to failure t_F is recorded at the end of the test. The minimum displacement rate, noted $\dot{\delta}$, was obtained by the time derivative of the displacement measured experimentally. All these parameters are useful for the following interpretation.

3. Modelling

3.1. Finite element modelling

The width of the ring was chosen to ensure that plane strain conditions were fulfilled during the test. To check this, a finite element calculation was run to simulate the crack growth within the 3D meshes corresponding to the NOL ring and half cylinder. A damage based constitutive model was utilized (Laiarinandrasana et al. (2011b)) to properly simulate the curvature of the crack front. Figure 2 illustrates a quarter of the specimen tested. The damage contour map on a deformed specimen is shown. Furthermore, a routine allowing the removal of elements which exhibited a critical porosity of 50 % was applied. The right figure shows a zoom on meshes in the net section. The crack front is curved only near the surface. Therefore, the specimen could be considered as being under plane strain conditions. Calculations of the load parameter C*-integral could then be carried out in 2D with plane strain conditions.

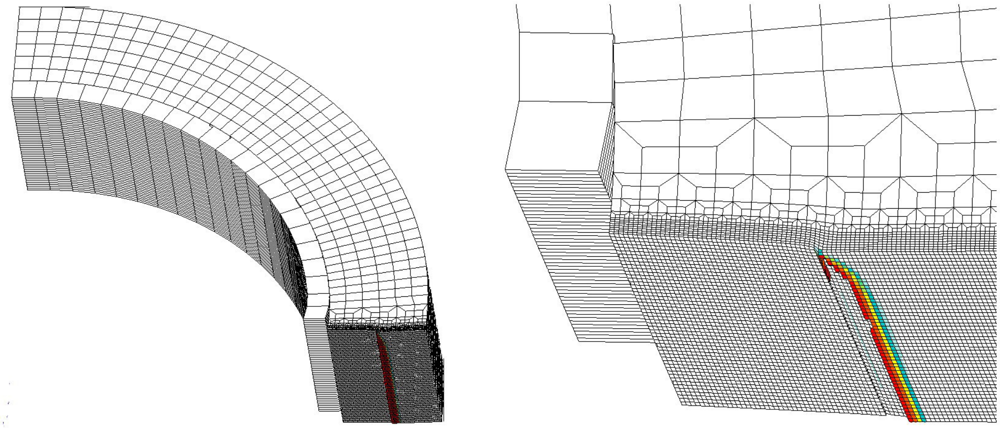

Fig. 2. Deformed 3D meshes of the NOL ring specimen: (*Left*) Damage contour map on the overall quarter geometry; (*Right*) Focus on the crack tip showing crack advance

3.2. Master curve: t_F-C* correlation

A master curve was previously proposed by Devillers (2011), by using creep crack growth tests on double edge notched tensile (DENT) specimens. Such a master curve correlates the time to failure t_F to the C* integral defined as:

$$C^*(DENT) = \frac{1}{2}\frac{n_2 - 1}{n_2 + 1}\sigma_{net}\dot{\delta} \tag{1}$$

where:

- n_2 is the creep exponent of the material creep behaviour;
- $\dot{\delta}$ is the opening displacement rate.

No closed formula is available for precracked NOL ring specimens. Since the same HDPE material is addressed here and σ_{net} as well as $\dot{\delta}$ were measured experimentally, the same formula as in eq. 1 was utilized.

Figure 3 shows up the excellent correlation between t_F and the C*-integral for all creep crack growth tests on two different specimens. This clearly highlights the relevance of the present master curve for predicting the residual lifetime of a cracked body subjected to a steady load.

3.3. Methodology to predict residual lifetime

The durability assessment requires two major ingredients:

- a master curve such as the one depicted in fig.3;
- a methodology allowing for C*-integral for the cracked body.

The in-service HDPE pipes are likely to contain longitudinal infinite internal defects due to the oxidation. The guidelines to calculate the C*-integral for such an engineering structure is provided in Marie et al. (2007). Once the C*-integral is determined, the master curve in fig.3 allows for the prediction of the residual lifetime t_F. Planning the replacement of degraded pipes can then be established by giving priority to pipes exhibiting the minimum values of t_F.

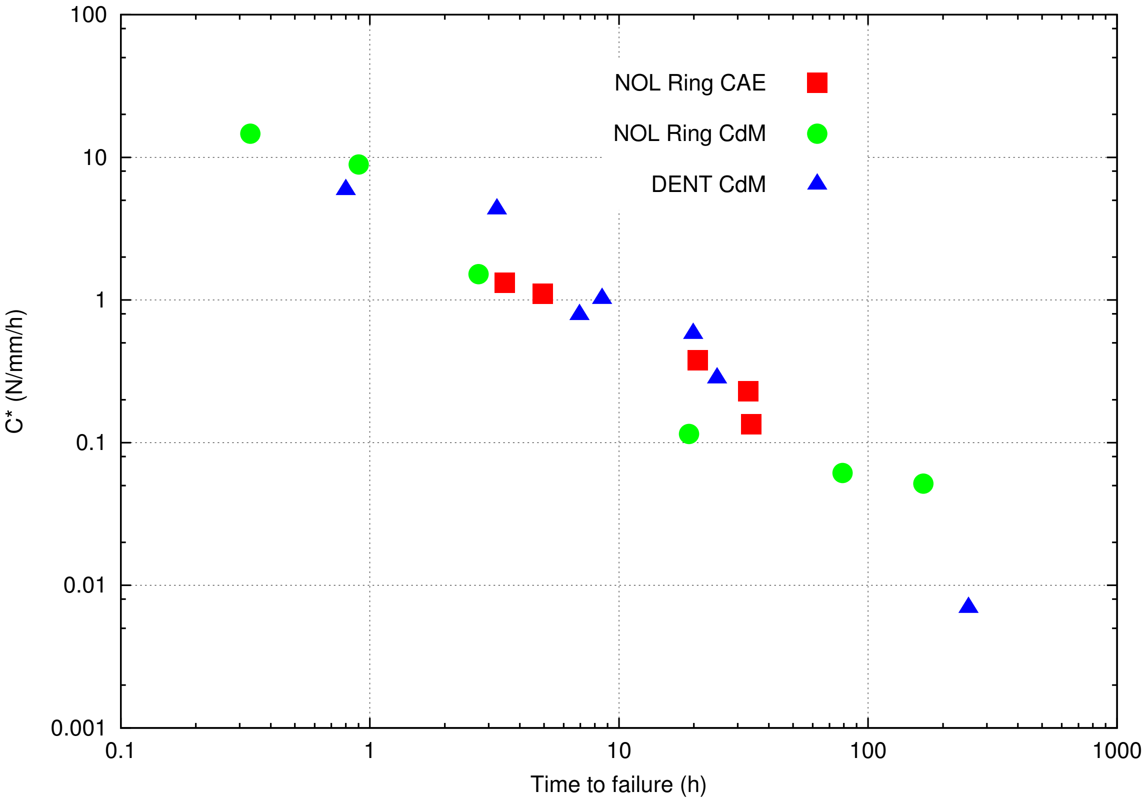

Fig. 3. t_F-C* correlation for CAE and CdM creep crack growth tests.

4. Conclusion

HDPE pipes used for the distribution of drinking water are subjected to oxidation in their internal wall by the disinfectant. This oxidation leads to chain scission in an internal layer of material and causes the appearance of a network of cracks. If the depth of one of the longitudinal cracks reaches 20 % of the thickness it is likely to propagate under a creep loading. In addition to a previous master curve obtained from DENT specimens, the present work highlighted that with an original cracked geometry (NOL ring) the time to failure *versus* the C*-integral correlation is very accurate. This has been used to planify the replacement of defected pipes that are still in service.

References

Devilliers, C., Laiarinandrasana, L., Fayolle, B., Gaudichet-Maurin, E., Oberti, S., 2009. “Impact of chlorine dioxide on the microstructure of polyethylene pipes: study of a crack network,” 14th International Conference on Deformation, Yield and Fracture of Polymers, April 5-9, 2009, Rolduc Abbey, Kerkrade, the Netherlands.

Laiarinandrasana, L., Devilliers, C., Oberti, S., Gaudichet-Maurin, E., Fayolle, B., Lucatelli, J.M., 2011a. Ring tests on high density polyethylene: full investigation assisted by finite element modelling. International Journal of Pressure Vessels and Piping 88, 1–10.

Laiarinandrasana, L., Ben Naceur, I., Besson, J., Jeridi, M., Cailletaud, G. 2011b. Multi-mechanism damage-plasticity model for semi-crystalline polymer: Creep damage of notched specimen of {PA6}. Materials Science and Engineering: A 528, 1087–1093.

Devilliers C. 2011. PhD thesis Ecole Nationale Supérieure des Mines de Paris. *in french*.

Marie, S., Chapuliot, S., Kayser, Y., Lacire, M.H., Drubay, B., Barthelet, B., Le Dellioud, P., Rougiere, V., Naudin, C., Gilles, P., Triay, M. 2007. French RSE-M and RCC-MR code appendices for flaw analysis: Presentation of the fracture parameters calculationPart III: Cracked pipes. International Journal of Pressure Vessels and Piping 84, 614–658.